

Transport of Gas and Solutes in Permeable Estuarine Sediments

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LONG-TERM GOALS

The long-term goals of this project are to 1) quantify gas bubbles and their composition in shallow nearshore marine sand and 2) to assess the role of gas bubbles in shallow sandy coastal sediment for the transport of solutes through the sand and sediment-water exchange of matter. Due to their compressibility, gas bubbles embedded in shallow water sediments cause interstitial water oscillations under passing surface gravity waves, and these oscillations provide a mechanism for enhanced solute dispersion and flux.

OBJECTIVES

- 1) To detect gas bubbles and in coastal and estuarine sand deposits and to assess temporal and spatial distribution of sedimentary bubbles in sublittoral beds including sands inhabited by microphytobenthos and seagrass.
- 2) To quantify the size range and composition of the gas bubbles in the sediment and the overlying water.
- 3) To determine the volume change and migration velocities of interstitial bubbles and the links to pressure oscillations
- 4) To assess dispersion and transport of solutes caused by bubble volume change and migration under different pressure conditions.

APPROACH

Measurement of gas release volumes from the sediments using benthic chambers and gas analysis.

Release rates and volumes of gas released from the sandy sediments are measured using benthic advection chambers. The advection chamber is a benthic flux chamber that generates a defined pressure gradient at the sediment-water interface, which can be adjusted to mimic the natural pressure gradients as imposed by the interaction of boundary layer flows and sediment surface topography. Free gas accumulating in the chambers is extracted at the end of the incubation period with gastight syringes. The volumes of sampled gases are measured in calibrated capillaries, and the in-situ volume will be calculated for the hydrostatic pressure recorded at the water depth of the chamber deployment.

Determination of gas composition. The composition of the sampled gas volumes will be analyzed using a Gas Chromatograph (GC). The composition of the gas will permit identification of the processes that produced the gas (i.e. photosynthesis (O₂), heterotrophic activities (CO₂),

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 2008		2. REPORT TYPE		3. DATES COVERED 00-00-2008 to 00-00-2008	
4. TITLE AND SUBTITLE Transport of Gas and Solutes in Permeable Estuarine Sediments				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Florida State University, Department of Oceanography, 117 N Woodward Ave, Tallahassee, FL, 32306-4320				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

denitrification (N_2 , N_2O), sulfate reduction (HS^-), and methanogenesis (CH_4) and thereby also confine the layer where this gas was generated.

Measurement of gas bubble dimensions and distribution. Bubble size analyses are performed on sediment cores maintained at in-situ pressure, light and temperature and without changing the orientation of the core. Images produced using a digital microscope permits inspection of the samples and show the spatial distribution of bubbles in the core.

Mapping of the spatial and temporal distribution of high sedimentary photosynthetic production and oxygen supersaturation and depletion as potential sites for free gas development. Measurements with an in-situ fluorescence detector and an oxygen microprofiler are used to map areas of benthic photosynthetic oxygen production. The measurements along transects perpendicular to the shore line shows the zone of maximum benthic photosynthetic activity which generally is confined by light intensity, nutrient availability, the rate of sediment mixing and the rate of grazing by herbivores. Oxygen concentration in the sediment surface layer, levels of supersaturation as well as the upper boundary of oxygen depletion are assessed through in-situ oxygen microprofiles conducted with the MicroTX3 system. The oxygen microsensor (sensing tip diameter 100 μm) is connected via a fiber optic cable to the MicroTX3 and is lowered with a micromanipulator at 200 μm depth increments into the sediment. The profiles identify sediment layers oxygen supersaturation and potential bubble formation.

Determination of the rate of gas bubble release from the sediment through quantification of noble gas depletion in the pore water. Depending on the rate and volume of bubble release (ebullition) from the sediment, the pore water will show reduced concentrations in dissolved atmospheric noble gases. The poorly soluble noble gases diffuse into the gas bubbles and are released from the sediment during ebullition of bubbles. The volume of gas released from the sediment by ebullition, thus, can be calculated from the extent of the noble gas depletion in the pore water using a simple gas-equilibration model. With the GC, we can measure the composition of the sedimentary gases including the noble gases. Pore water profiles of noble gases then can be compared with the volume of free gas detected in the sediment.

Determination of gas content, distribution and migration in the surface sediment. Content, distribution and migration of free gas in the surface layers of the sand sediment is investigated with a tunable ultrasound square wave pulser, with measurement rate adjustable from 10 Hz to 1000 Hz in 10 Hz increments connected to one sending and one receiving high-frequency transducer (1-30 MHz). Attenuation of the high-frequency sound pulses required for the detection of small bubbles within the sediment is large in sand beds, thus, the sending and receiving transducers have to be moved into the sediment in order to reach deeper sediment layers. The intrinsic compressibility of microbubbles is approximately 17,000 times more than water, and they are very strong scatterers of ultrasound (Anderson and Hampton 1980a). Microbubbles increase the Doppler signal amplitude by up to 30 dB. Because the attenuation of the sound signal peaks at the resonance frequency of the bubbles, it is possible to assess bubble size by using scans of different sound frequencies (Anderson and Hampton 1980b; Best 1997)

Measurement of solute transport caused by bubble compression and migration. In shallow water, the volume change of sedimentary bubbles due to pressure oscillations can be significant due to the high relative pressure changes. Wave-induced bubble volume oscillation thus can cause pore water transport and dispersion. This process is investigated in a laboratory column setup which allows measurement of

the migration behavior and velocities of gas bubbles in permeable sandy sediments under the influence of sinusoidal pressure oscillations and determination of transport rates, dispersion and interfacial flux of solutes and colloidal material.

Participating Scientists and students. Scientists and students participating in this work are Dr. Markus Huettel (PI), Dr. Parthasarathi Chakraborty (Postdoc), Sucharita Chakraborty (graduate student), Veronica Cruz (undergraduate student) and Allison Rau (undergraduate student).

WORK COMPLETED

Two field campaigns were conducted, the first in April 2008, the second in August 2008.

The goal of the first campaign was to determine whether methane production causes gas bubble formation in Wakulla River Estuary sand sediments, and to assess whether methane is released from the sediment as bubbles. Seven benthic chambers and one ADV with oxygen Optodes were deployed at the study site in the Wakulla River (Fig. 1) and measurements were conducted over a 24 h period. This section of the river is affected by the tidal cycle in the nearby Gulf of Mexico and water level and flow velocity vary accordingly. Optical sensors in the chambers recorded oxygen concentration and light and temperature loggers monitored PAR and water temperature. At the end of the deployment, the chambers were inspected for gas ebullition.

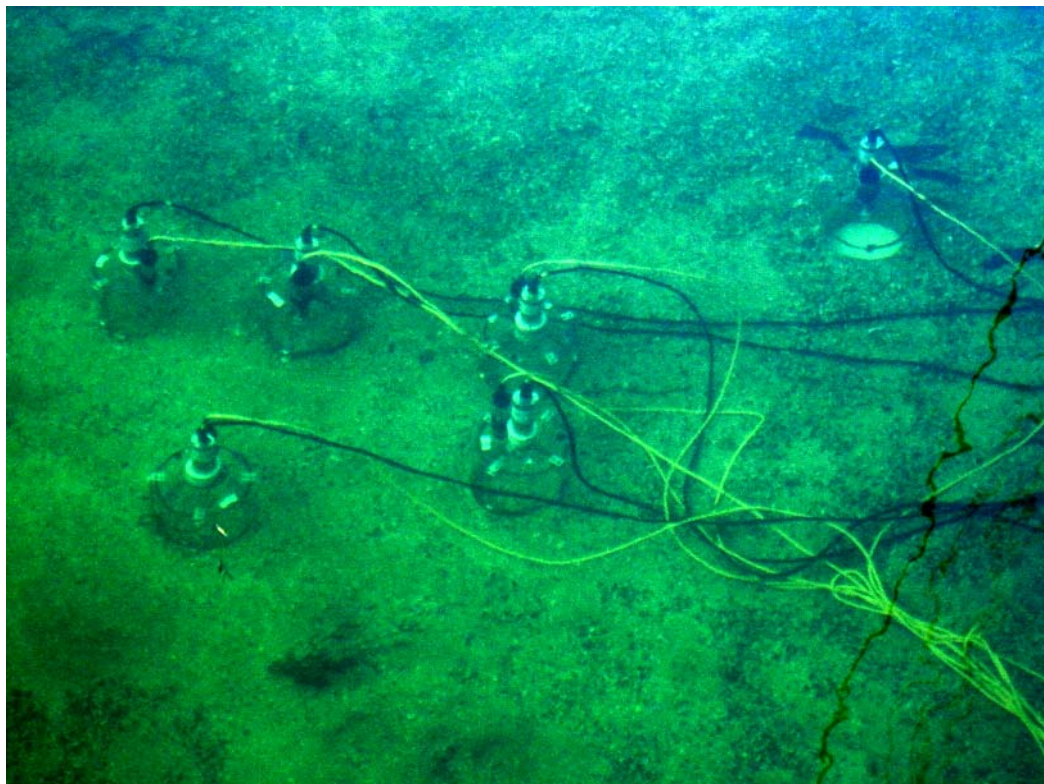


Fig. 1 Advection chambers deployed on gassy sediment in the lower Wakulla River. The chamber on the upper right is the reference chamber and does not contain sediment.

The second field campaign was conducted in the sublittoral zone off St. George Island in the Northeastern Gulf of Mexico. Goal of this campaign was to measure gas production in permeable sediment inhabited by microphytobenthos (diatoms, cyanobacteria) that are able to generate large amounts of oxygen in the surface layer of the sediment. Seven benthic chambers were deployed at the study site and measurements were conducted for a period of 6 h. Oxygen Optodes followed oxygen concentration in the chambers and calibrated PAR sensors installed at the sediment surface recorded light intensity. Reference sensors at the surface permitted calculation of light attenuation by the water column. Concurrent temperature and salinity recordings allowed calculation of oxygen saturation values. Time lapse photography was used to monitor the accumulation of the gas bubbles in the chambers. Sediment cores retrieved from the study site were incubated in the laboratory in order to determine oxygen production under defined light conditions.

RESULTS

The chamber deployment in Wakulla River did not show gas ebullition from the sediment. However, large volumes of methane were collected in the chambers when removed from the river bed. During removal, a sediment column of 15 cm depth and 283 cm² area (volume 4245 cm³) of sand is sampled by each chamber. These sediment cores collected by the chambers showed thick subsurface methane accumulations that formed gas layers up to 2 cm thick at 3 to 10 cm sediment depth. This gas was collected in the chambers and the volume was determined (Fig. 2)

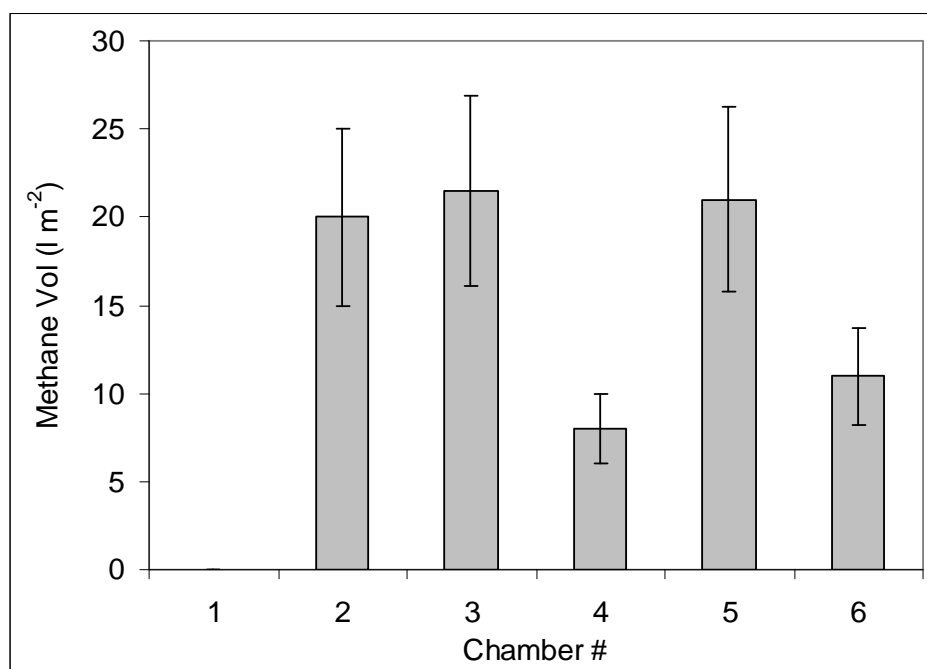


Fig. 2. Methane volumes recorded in the upper 15 cm of Wakulla River sediment. These measurements were done on site by measuring the size of the methane layer accumulating in the chambers when gas was allowed to bubble out of the sediment enclosed by the chamber.

These massive layers of methane are supported by microbial degradation of wood and other plant materials that are embedded in the coarse sand sediment. This site will be used for the testing of our gas bubble quantification methods and will provide sediment cores for our laboratory experiments.

The chambers deployed in the shallow nearshore Gulf of Mexico showed rapid gas accumulation caused by benthic primary production (Fig. 3).

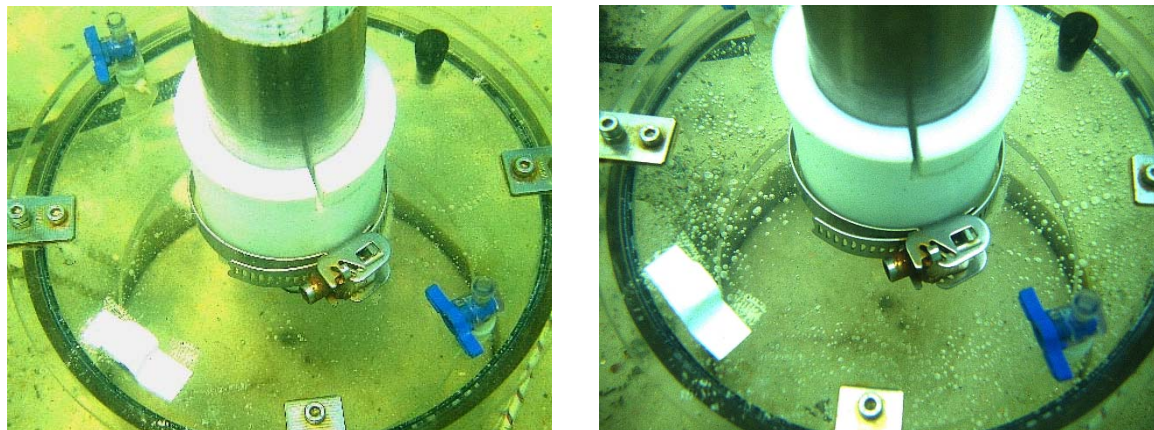


Fig. 3. Evolution of gas bubbles in the chambers deployed in the sublittoral at St. George Island. The image on the left shows small bubbles 4 h after start of the deployments, the right image a large number of bubbles at the end of the deployment (6 h).

The gas bubble volumes increased exponentially in the chambers and at the end of the deployment reached a volume of $361 \pm 297 \text{ ml m}^{-2}$ (Fig. 4).

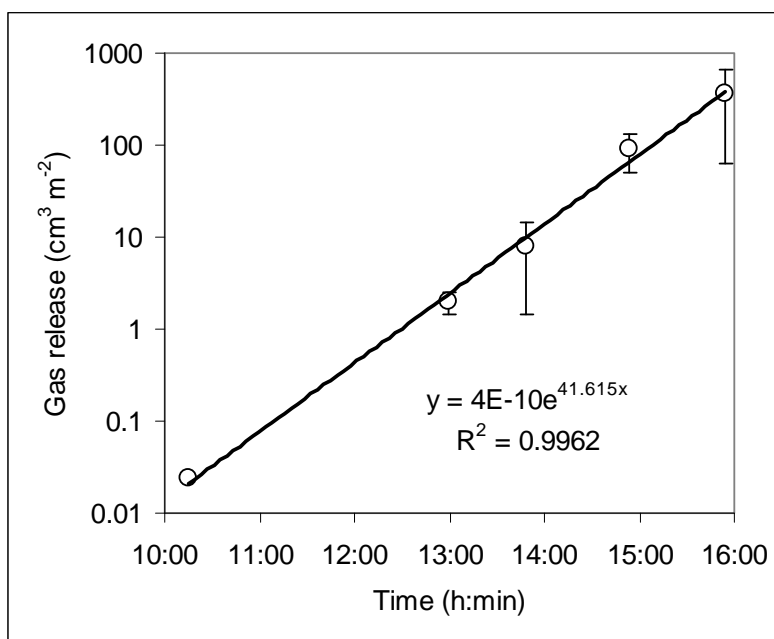
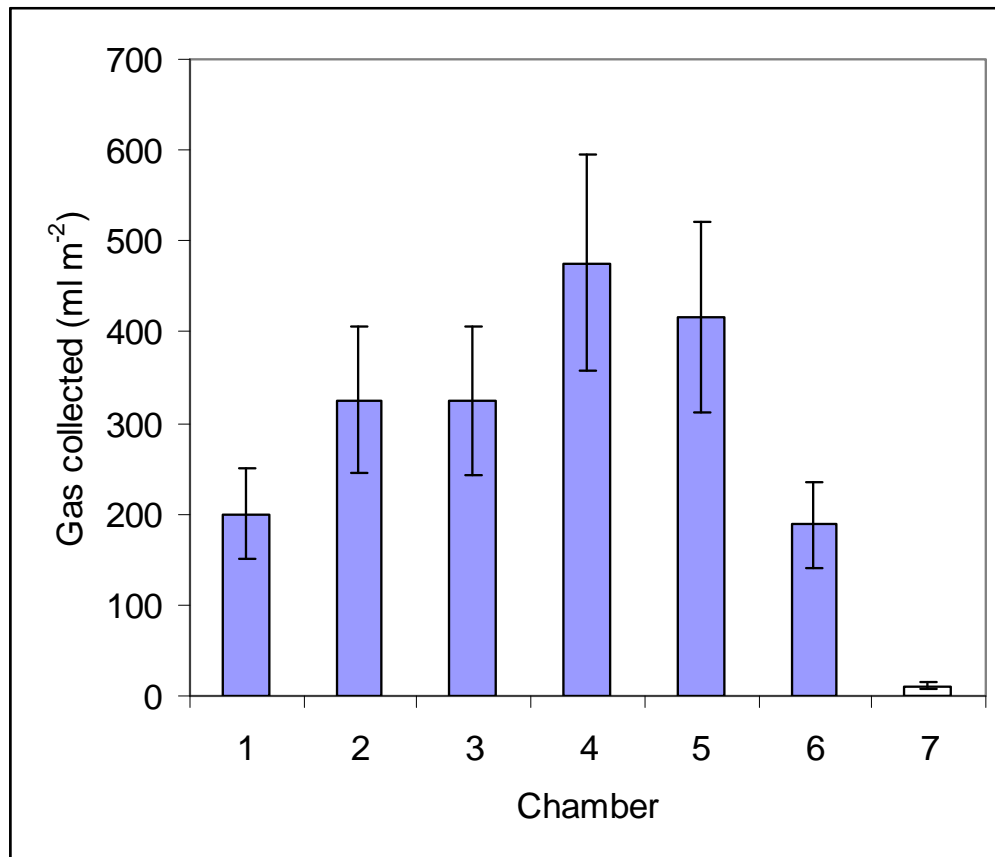


Fig. 4. Increase of gas volume in the chambers over time. At the beginning of the experiment, only very few small bubble could be detected that likely were released from the sediment while pushing the chambers into the sand.



***Fig. 5 Gas collected from the chambers after 6 h (end of deployment).
Chamber 7 did not contain sediment.***

The variability of the gas production likely is caused by different density of the microphytobenthos assemblage. The latter, composed mainly of diatoms and cyanobacteria, is heavily grazed upon by a variety of benthic organisms including echinoderms, crustaceans, mollusks, polychaetes, and ciliates. This grazing and lateral sediment transport due to ripple migration affects the distribution of the microphytobenthos, causing patchiness and likely also the uneven gas production observed in the chambers.

If the primary source of the gas collected in the chambers is benthic photosynthesis, then it could be assumed, that the collected gas would contain mostly oxygen. This was not the case, the gas rather had oxygen and nitrogen concentrations that were in equilibrium with the partial pressures of the ambient seawater. As the gas bubbles were exposed to the seawater for a period of several hours, gas exchange between the bubbles and the seawater led to an equilibration resulting in a gas composition similar to that of the water in the chambers. Noteworthy is the low concentration of carbon dioxide in the gas samples, which is a result of the effective uptake of carbon dioxide by the photosynthesizing community.

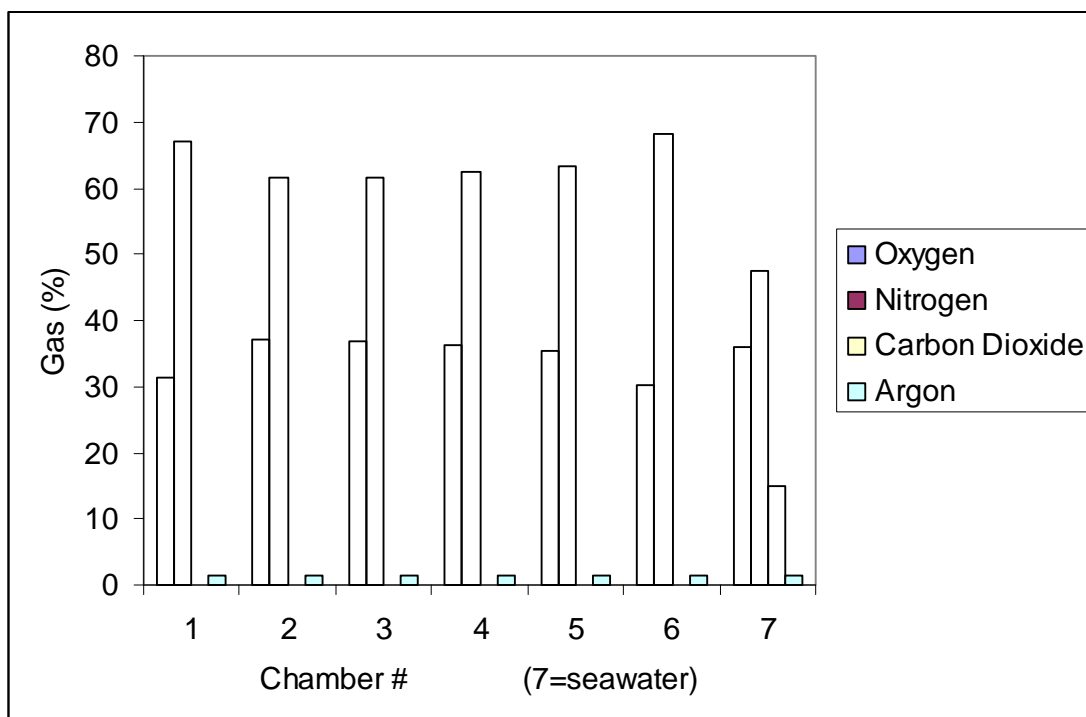


Fig. 6. Composition of the gas extracted from the chambers analyzed in a gas chromatograph with thermal conductivity detector. Sample 7 shows the gas concentrations expected for shallow sea water.

Our results demonstrate the high potential for free gas production in shallow estuarine and coastal permeable sediments. This high potential is closely linked to the physical characteristics of these sediments promoting filtration of particulate organic matter and reactive solutes in the surface layers of the bed. Gas producing organisms benefit from this filtration, i.e. methanogens from the filtration of organic particles and oxygen-producing phototrophs from the enhanced supply of nutrients and carbon dioxide. The high rates of biological activity result in local supersaturation permitting the generation of gas bubbles in the pore space.

IMPACT/APPLICATIONS

Increasing nutrient and organic matter concentrations in coastal and estuarine systems caused by anthropogenic activities enhance the microbial activity in shallow sediments promoting gas production and ebullition. We therefore expect an increase in the occurrence of free gas and ebullition from riverine, estuarine and coastal deposits. As a large fraction of these environments is shallow (<10m), boundary layer currents produced by wind, tides and density gradients in these areas are strong resulting in coarse grained sediments. This research promotes science addressing the changes in physical and biological characteristics of nearshore permeable sediments that are among the ecosystems most severely affected by anthropogenic activities but at the same time the most influential for coastal water quality and coastal production. The latter closes a positive feedback loop between the primary production process and the free gas development and ebullition, as the compressible gas bubbles enhance pore water exchange and nutrient release from the sediment, and up-moving bubbles provide a pump moving nutrients up into the water column further fueling primary production. A

quantitative understanding of the free gas dynamics in these systems, thus, is essential for the prediction of future physical and biological characteristics of these sediments.

TRANSITIONS

At this initial stage of the project, there are no outside users of the project results.

RELATED PROJECTS

NSF project “Quantifying dissolved organic matter degradation in filtering shelf sands”

In this project we are testing the hypothesis that degradation rates of dissolved organic matter (DOM) in filtering shelf sediments exceed those in the overlying water column. Although a large fraction of the terrigenous DOM is refractory, it does not accumulate in the shelf and oceans. Objectives of the proposed research are 1) quantification of DOM degradation in filtering Gulf of Mexico sands and overlying water 2) assessment of the influences of pore flow velocity, temperature, oxygen concentration and light on DOM decomposition rates, and 3) characterization of DOM compositional changes caused by sediment passage. The results are expected to show whether DOM filtration through permeable sediments can significantly contribute to the DOM sink in the shelf. Sedimentary DOC degradation can cause oxygen deficiencies and gas production, and can mobilize nutrients enhancing primary production and oxygen evolution.

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